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Transportation Network Post-Disaster Planning and Management: A Review Part I: Post-Disaster Transportation Network Performance

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Abstract

In recent years, disasters have an increasing impact on modern societies in terms of both economic and human losses. Following disasters, transportation networks act as key lifelines enabling access to the affected communities and supporting evacuation, emergency response, relief and recovery operations. In this context, this two-part survey offers a systematic review of papers related to transportation network post-disaster planning and management. A classification of existing work in two categories is proposed: first, is estimation of post-disaster transportation network performance and second, is decision-making and planning of post-disaster operations. This paper constitutes the first part of the survey focusing on post-disaster network performance evaluation, highlighting important aspects of the problem and proposing potential avenues for future research. The second part of this survey addresses the problem of post-disaster network management.

Keywords: *transportation network post-disaster planning, network performance assessment, failures, vulnerability, reliability, dependencies*

1. Introduction

Disasters have always been a major concern for societies due to their impact on human life and activities. Hurricanes, floods, earthquakes, bomb-attacks and other phenomena or incidents may cause extended damages to infrastructures, loss of lives and disruption of human activities. The impact of disasters on society and the economy has increased in the recent years; factors such as the size and density of modern communities and their dependence on sophisticated yet sensitive infrastructures, have critically contributed to populating effects of catastrophic events. Transportation networks are identified as critical lifelines in cases of disasters for a number of reasons: first, the transportation system will support evacuation, emergency response, relief and recovery operations. Second, the transportation network will remain the sole means for ensuring physical access to the affected communities. Third, transportation infrastructures are highly prone to disasters and therefore their capacity and serviceability will be reduced following a catastrophic event.

Disaster management refers to those tasks related to assessing the risks and mitigating the impacts of catastrophic events on transportation networks. In this context, disaster management involves a chain of activities, ranging from performance evaluation and pre-disaster improvement of network resilience to post-disaster response, recovery and re-construction [40]. These activities are inevitably characterized by uncertainty, a result of the unforeseeable characteristics of disasters and their impacts on infrastructures and

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human activities. These facts alone imply that planning for disasters is a multi-aspect, stochastic process, targeting at different phases, before, during and following a catastrophe. The difficulties arising in this context have also been of interest to the Federal Highway Administration (FHWA) which as [58] note "…recognizes the unique challenges posed by the disaster environment on mobility and the safe and secure movement of people and goods". In the same study, [58] accentuate the importance of the transportation network's availability and capacity in emergency response and evacuation operations. Indeed, post-disaster conditions in a transportation network remain uncertain, while the disaster's aftermath depends on the serviceability of the "surviving" network and its capacity to support evacuation, emergency response, relief and recovery operations. In that sense, efficient tools for planning and managing post-disaster transportation network operations are of significant practical importance.

This two-part survey focuses on post-disaster planning and management of transportation networks and offers a structured, critical review of over 120 published papers in that area. This paper constitutes the first part of the survey and investigates existing work on transportation network performance following a catastrophic event. Network performance studies are classified on the basis of specific categories of characteristics regarding the disaster environment where the problem unfolds and their general conceptual approach. Based on the review outcomes, literature gaps and potential future research areas are identified and discussed. Different aspects of planning post-disaster network operations are the subject of the second part of this survey. The objective is to offer an integrated, comprehensive view of the State-of-the-Art (SoA) on post-disaster transportation network planning and management to interested parties and highlight potential topics in need of further research in this area.

The remainder of this paper is organized as follows. Section 2 provides a description of disaster planning in transportation networks and Section 3 focuses on post-disaster network planning. The problem is distinguished into two distinct parts: network performance and planning of post-disaster network operations, corresponding to the research subject of this paper and the second part of the survey respectively. Section 4 systematically reviews publications on post-disaster network performance (PDNP) estimation. Section 5 offers a discussion on the PDNP and the paper concludes in Section 6.

2. Disaster Planning in Transportation

According to [40], "disaster management is a multi-stage process that starts with pre-disaster mitigation and preparedness that focus on long-term measures for reducing or eliminating risk, and extends to post-disaster response, recovery and re-construction". The pre-disaster planning phase therefore, involves strategic decision-making for risk assessment and infrastructure improvements to reduce vulnerability and enhance human and physical system resilience. The post-disaster stage involves performance estimation and tactical and operational decision-making for providing critical emergency, recovery and re-construction services. It should be stressed in advance, that pre- and post-disaster phases refer to the actual timing of planned actions and not necessarily to the decision making process. For instance, emergency plans are prepared in advance but applied in the post-disaster phase while performance assessment of transportation infrastructures is required for improving their survivability against catastrophic events. An outline of the disaster planning process is depicted in Figure 1.

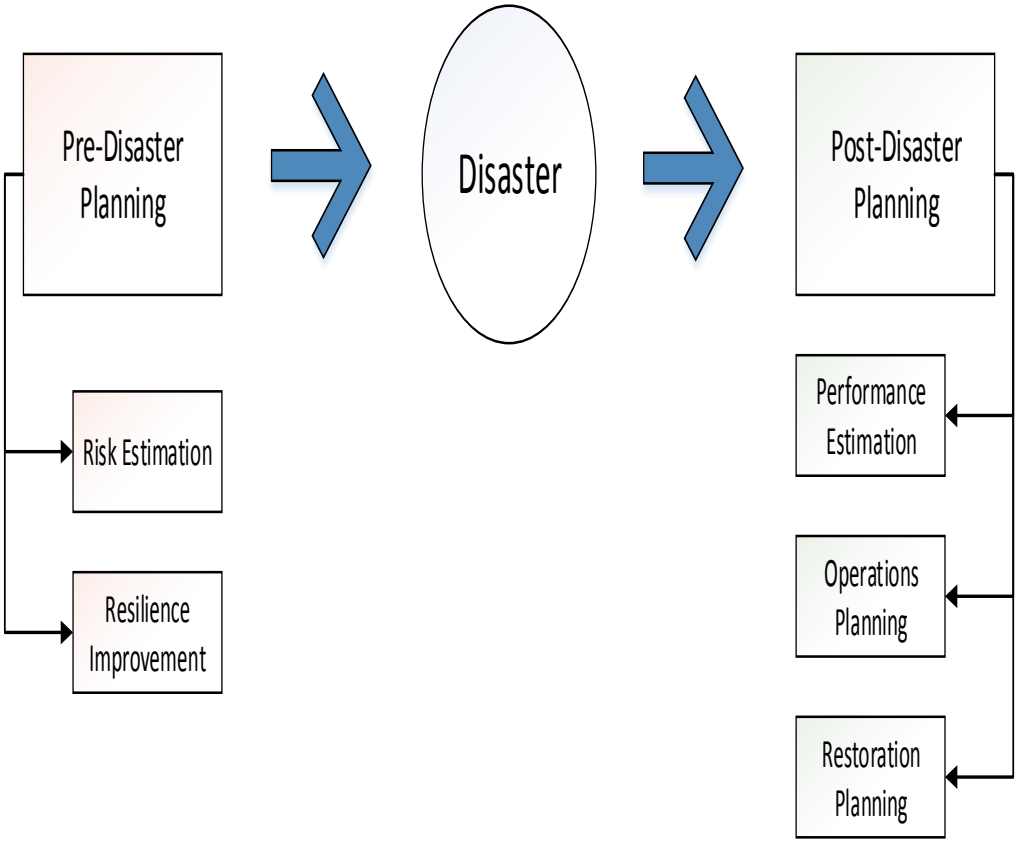

Figure 1. The Disaster Planning Process

In this context, [14] indicate four major courses of action in the disaster planning context: (a) the identification of network elements prone to disasters, (b) their impact on operations and protection requirements, (c) the establishment of resilient infrastructures and (d) the scheduling and allocation of recovery resources. Cases (a)-(c) are part of the pre-disaster planning phase: risks in the transportation network elements and infrastructures are to be identified and upgrade and retrofit actions for improving the survivability of a transportation network are scheduled and planned. Planning in the pre-disaster phase is mostly preventive; apart from the design of new, failure-resistant infrastructures, investment decisions in the form of reinforcement or retrofit actions allow the structural integrity and survivability of network components to be enhanced [40]. Experience has shown however that prevention tasks may be inadequate; both the characteristics (magnitude, space and time extent) of a catastrophic event and the performance of infrastructures are uncertain. In addition, limitations in resources make an extensive deployment of plans for enhancing resilience infeasible, raising thus the need for a criteria-based prioritization of retrofit activities [40].

In the post-disaster phase, the transportation network may suffer severe damages to its elements (highways, bridges, embankments, tunnels), ranging from degradation to full collapse. These may in turn reduce the network's performance, limit its connectivity or lead to partial loss of functionality. The "surviving" transportation network will be expected to operate under a completely different operating environment and service needs. An impending disaster may, for example, force the evacuation of population. The network should be able to handle the large volumes of outbound traffic but at the same time reserve some lanes and routes for emergency response and relief activities. In a later stage, the same network is expected to support recovery but also daily activities until its full restoration. In this context, post-disaster planning focuses on related response,

recovery and restoration actions, which would support evacuation and emergency logistics services and gradually restore network operations to their normal condition.

The post-disaster phase can be distinguished into sub-phases according to the timing, status and role of the network [19]:

1. *"During-the-disaster" operations (response) sub-phase:* During and shortly after a disaster, the surviving network will support emergency operations. Thus, focus is given towards operating transportation networks in such a way that priority is given to emergency response unit access and possibly population evacuation. At this phase, normal community activities are more or less disrupted and regular transportation needs are minimal. [19] refer to that phase as "Confusion" and "Settlement" states.
2. *"After-the-disaster" operations (recovery) sub-phase:* In the period following the direct aftermath of a disaster, community activities will gradually recover; the same applies to damaged transportation infrastructures, which should be restored. At that phase however, the surviving network should still have to provide services to the community, while being restored. According to [19], this is the "Stability" state.

It is important to note that there exist different planning requirements for the two post-disaster sub-phases: "during-the-disaster" priority is given to emergency response and evacuation while "after-the-disaster" normal network operations should be re-instated in parallel to network restoration activities. Pre- and post-disaster planning tasks are interrelated; efficient pre-disaster planning produces more resilient transportation networks, which in turn have improved survivability chances under a catastrophic event. In turn, potential post-disaster network operations set an additional criterion for prioritizing network improvement activities; for instance, network elements of secondary operational importance may be given less attention in infrastructure retrofit programs, particularly in the case of budget constraints. As such, preparing for post-disaster network operations is equally critical and a necessary supplement to enhancing the strength and survivability of its elements in the pre-disaster phase.

3. Transportation Network Post-Disaster Planning

Post-disaster planning may involve different operational tasks including evacuation, emergency traffic management, emergency logistics deployment, recovery oriented resource allocation and restoration project programming. Such tasks may be prepared as parts of proactive plans or reactive and therefore decided, planned and implemented following a disaster. In both cases, planning requires an estimation of the post-disaster network performance (PDNP), which could then be used for decision making. PDNP would describe and/or assess post-disaster network conditions, as well as its survivability and functionality. A good estimate of PDNP can be used in a subsequent step for evacuation, response, recovery and restoration decision making; relevant actions will be planned based on estimates of the network's performance. In this context, the work on post-disaster network planning and management can be broadly divided into two categories:

1. Performance measurement and assessment of the post-disaster transportation network.
2. Decision making and planning of post-disaster network operations.

The first category comprises efforts and models for representing and estimating performance in a post-disaster environment. Their outcome is the description of the surviving transportation network, with respect to its level of structural integrity and functionality. As for the second category, it includes all decisions that need to be made with respect to the management of the surviving transportation network under conditions

of increased demand and possibly reduced capacity. It should be stressed out that a distinction is made between the actual management of the network and to emergency response, logistics and humanitarian operations supported by the network. Indeed, the former addresses the problem of improving service provision to network users of different categories, for example, establishing emergency and evacuation routes, managing traffic and restoring transportation infrastructures. As for the latter, it refers to actual emergency response activities which use the surviving transportation network for their own purposes; while these are also part of an overall disaster planning process, they do not focus on the operation of the transportation network but they rather exploit its services. As such, from a conceptual perspective, they are not considered at the core of the post-disaster transportation planning process.

4. Post-disaster Network Performance (PDNP)

Estimation and/or measurement of surviving network performance is an important, first step for planning post-disaster network operations. A total number of forty eight papers have been identified on that topic; the framework used for their categorization is shown in Figure 2.

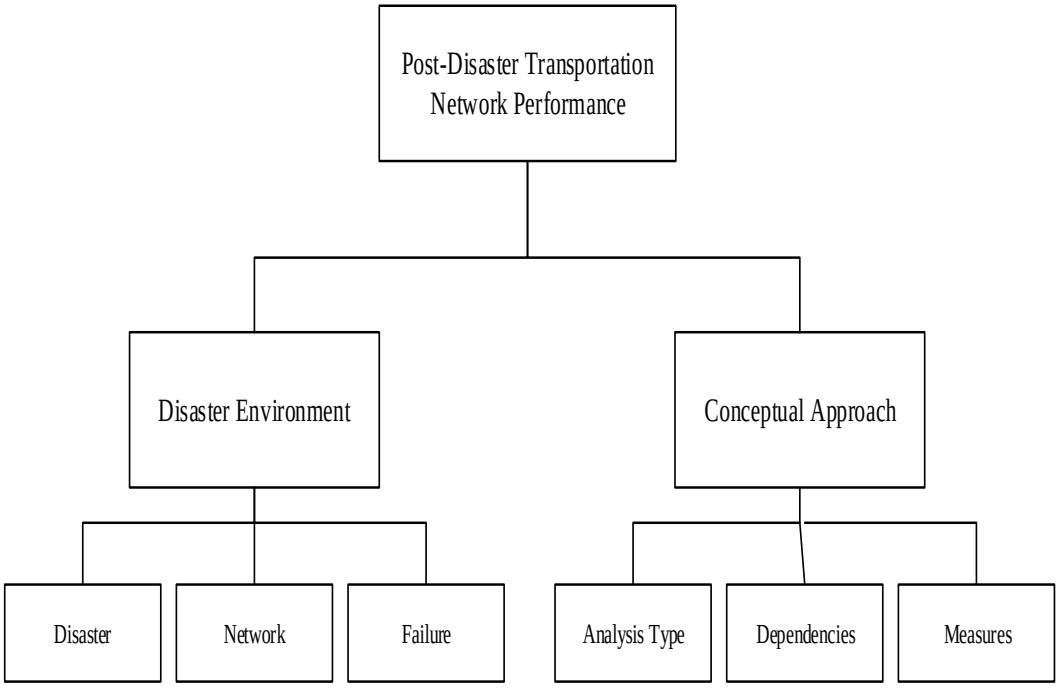

Figure 2. Categorization Framework

The proposed framework attempts to categorize reviewed papers according to two major aspects: (a) the disaster environment and (b) the conceptual approach used for estimating PDNP. In this context, assumptions made on the disaster and the affected network set the disaster environment. Factors such as the nature of the disaster, the characteristics of the network and the failure mechanisms are considered to be major players for setting up PDNP models. Having determined the disaster environment, performance estimation may be based on different conceptual approaches for representing and measuring PDNP. Modeling efforts are dictated by the type of analysis used, the possible interdependencies between network components and those measures used for quantifying PDNP. Using, that categorization, Table 1 provides a classification of existing work by considering the type of analysis performed along with assumptions made on the nature of component failure. Papers accompanied by a (*) imply that some sort of

dependency between the network components and their failure states is considered as part of the analysis. Table 2 illustrates indicative performance measures used in each one of the papers reviewed.

Table 1. Classification of Transportation Network Performance Studies

		Type of Analysis				
		Vulnerability	**Robustness**	**Resilience**	**Reliability**	**Risk**
Component failure extent	**Complete Failure**	[13], [21], [27], [34], [54], [56], [7], [23] (*), [20], [29], [32], [55], [43], [52], [22], [49], [53]	[28]		[17] (*), [40], [42], [39], [47] (*), [3], [38], [2]	[31]
	Partial Failure	[9], [6] (*), [4], [12], [24], [10], [11], [36]	[48], [50], [35]	[33] (*)	[1], [16] (*)	[25], [26] (*), [41] (*)
	Without Failure		[46]	[44], [51]		[15]

Papers accompanied by a (*) imply that some sort of dependency between the network components and their failure states is considered as part of the analysis.

4.1. Disaster Environment

The disaster environment sets the major underlying assumptions for defining and estimating post-disaster network performance; these briefly include the disaster considered (*e.g.*, earthquake, flood), the type of network investigated (highway, bridge etc.) and the number, extent and spatial distribution of network component failures.

4.1.1. Disaster Type: From a generic perspective, PDNP refers to the impact of a disaster and therefore it can be argued that the actual type of the disaster is irrelevant when estimating the post-disaster performance of the network. As such, many studies assume generic disasters (for example [54, 55, 35]). However, this is not the case when impacts are a function of particular disaster characteristics. For instance, [26] use earthquake ground motion to evaluate the structural and operational loss of a bridge network. In this case, the seismic event itself plays an important role into defining post-disaster performance. Similarly, [6] exploit earthquake fragility curves of infrastructures as inputs for analyzing PDNP. Overall, earthquakes are the most commonly considered disaster [34, 25, 26, 41], while some papers consider landslides and flooding [15, 49].

4.1.2. Network Characteristics: The type, role and characteristics of the transportation network do affect the disaster environment and the way performance is addressed. Indeed, assumptions on the network characteristics set the initial network configuration, its connectivity settings, the initial state of individual components and post-disaster requirements. For instance, rural networks exhibit lower traffic volumes and therefore post-disaster performance is in such cases related to accessibility (*e.g.*, [54]). From another perspective, different operations and limited connectivity and bypass options for railways may again lead to different performance interpretation. In this context, past

research has focused on *urban road networks* [13, 56, 7], *regional road networks* [54], *highway networks* [17, 32, 47] and *railway networks* [23, 10]. Furthermore, some researchers consider bridges to be the most vulnerable part of the network and under this assumption investigate *bridge networks* [34, 6, 24], implying that the possibility of failure is limited to bridges.

4.1.3. Failure Representation: A transportation network consists of different infrastructures, whose initial characteristics, condition, damage extent and spatial distribution dictate PDNP. In a network level analysis, these are typically represented as changes in the components (links and nodes) of the network. In that sense, most of the reviewed papers model disaster effects as impacts on links only, while only a few treat links and nodes independently. Indeed, impacts on nodes can be straightforwardly replaced by impacts on links; for example, [43] assume both link and node failures; a link failure is treated by removing that link from the network while a node failure is treated by removing all the links entering or exiting that node.

In the same context, post-disaster network conditions refer to the reduced or no serviceability of a link (or node); in most cases a binary state of operational / non-operational link is assumed. Nevertheless, such an assumption is not always accurate since a link may be partially functional, a state indicated by some sort of capacity reduction or distance increase *e.g.*, [10, 11]. [17] argue in favor of the complete elimination of partially operational links, stating that a partially damaged link may not be partially operational, due to the reluctance of using it. On the other hand, [16] explore the use of multiple link capacity degradation scenarios and [50] are averse to complete link removal for not being realistic and methodologically sound. In general, these two distinct cases of link (or node) failure treatment can be denoted as *complete* [56, 27, 52] and *partial* [48, 9, 6] *component failure* respectively.

4.2. Conceptual Approach

Based on the disaster environment, different approaches have been developed for estimating PDNP. The literature exhibits different approaches and performance measures, while dependencies between components are another parameter considered for that purpose.

4.2.1. Analysis Type: The type of analysis refers to the underlying concept and mechanisms used for expressing PDNP. Five such concepts are identified in the literature: vulnerability, reliability, risk, robustness and resilience; these are based on the definitions set by reviewed papers. It is noted however that even the same terms are not uniformly interpreted in the literature.

A concept often used for investigating the sensitivity of a network against disruptive events is *vulnerability*. When referring to a transportation network, it is often associated with *accessibility*, with the latter representing the ease of approaching a destination [37]. [5] and [12] define vulnerability as susceptibility to incidents leading to reduced serviceability and mobility. For [9], vulnerability is the reduction in network's performance in the case of a link disruption, while according to [23] vulnerability describes the extent of impacts resulting from an incident. [22] introduce two terms for interpreting vulnerability: "link importance" and "exposure". The first term incorporates the impacts of link failure on costs and capacity and the second term addresses low probability incidents and their impacts on travelers. Later, [20] introduces "regional importance", "expected total exposure" and "expected user exposure" as terms expanding his previously proposed terminology. [29, 53] and [54] consider vulnerability as the impact of a failure instead of its occurrence probability.

Reliability is the probability of successfully travelling between points of the network while considering the likelihood of a disruption and its possible consequences [5].

Reliability is expressed in three ways ([5], [1]): (i) *connectivity reliability*: the probability of a path existence between two points, *(ii) travel time reliability*: the probability of reaching a destination within a time threshold and *(iii) capacity reliability*: the probability that a network is able to accommodate a certain amount of traffic when subjected to disruptions.

According to [22], travel-time reliability is user oriented, as it depends on network performance expectations, whereas connectivity is more of a theoretical concept. However, since the concept of reliability is so probability-dependent, [29] point out that a false estimation of these probabilities may well result in inaccurate reliability estimations. [52] and [53] illustrate differences between vulnerability and reliability. They report that a network may be reliable yet highly vulnerable at the same time, if failure probabilities are small but failure impacts are substantially high.

Another concept closely related to reliability is *risk*. Risk is associated with the probability of a disruptive event and its impacts [5]. In networks, risk is often defined as the combination of these two components [22]. [52] and [53] note that while vulnerability focuses on impacts, reliability and risk are concerned with the probability of disaster occurrence and consequences.

Robustness is an opposing term to vulnerability as it describes a network's strength [48, 27]. According to [50], robustness is the degree to which a network can retain its performance when subjected to link capacity disruptions. [28] associate robustness with connectivity reliability and accessibility. [27] consider robustness as the network's ability to preserve its functionality under conditions that "deviate from the normal". [48] note that "robustness is the extent to which, under pre-specified circumstances, a network is able to maintain the function for which it was originally designed". They also indicate that robustness is related to impacts of a disruption rather its occurrence probability and argue that robustness relates to less frequent events of increased impacts.

Resilience expresses the network's ability to regain its normal function after a disruptive event [5]. [48] define resilience as a "temporary overload" of the network. [33] indicate that resilience is not limited to the network's ability to handle a disruption but includes short-term, remedial actions for its restoration. [62] develop a measure for resilience in a multi-disaster environment. Based on the work of [8, 60] and [61], the authors extend the notion of single-disaster resilience to that of multi-disaster predicted resilience. [44] offers a framework for evaluating security resilience and argues that resilience should be examined in the context of weighted network topology/connectivity.

4.2.2. Dependencies: As transportation networks are large scale, spatially distributed systems, they do exhibit various functional and spatial dependencies between their components and interdependencies with other infrastructure systems [57, 30]. This implies that failures may cascade both among transportation network components as well as between the transportation network and other lifelines [23]. For instance, collapse of electricity pylons next to highways could lead to partial or even full road closures and reduce the functionality of the transportation network links. In this context, [18] and [45] distinguish dependencies between components of the same network from interdependencies between different networks. [23] point out that there is a need to specify whether the assumed interaction is treated on the macro-level (between systems) or on the micro-level (between system components) and whether it has a bi-directional or a uni-directional form. In general, the terminology presents inconsistency across the literature; the terms "dependencies" and "interdependencies" are used interchangeably in some studies while in others indicate a difference in the nature of the interaction [23].

The literature exhibits different ways of characterizing dependencies; [45] categorize them as physical (input-output dependence between components or systems), cyber (information transmission dependence), geographical (neighboring components affected by the same local event) and logical (all other types). [59] propose a broader

categorization, where dependencies can be viewed as functional and spatial (with the latter referring to geographical dependencies); the same categorization is adopted by [23] for modeling interdependencies in the case of vulnerability analysis of infrastructure systems.

With respect to transportation networks, the most common assumption in PDNP estimation is that transportation network components fail independently. Several researchers however argue that such an assumption is simplistic [16, 23]. Indeed, following a disaster, a network bridge may remain intact but its serviceability could be heavily reduced because of failures to neighboring infrastructures. [6] point out that when performance-based design and assessment is pursued for transportation networks, the damage state of individual components should be estimated having in mind that the overall network performance is a complex combination of them all. According to the same authors, the independence assumption between network components and their damage states can lead to significant errors when estimating network performance. However, the literature on the subject is still very limited [17].

Overall, only eight out of the forty-eight papers reviewed consider some sort of functional or spatial dependency between the components themselves and their failures. In [33] this has the form of correlation matrices between components while [16] use arbitrary values for the fractions of arc capacities between components. [47] try to expand the notion of correlation to "spatially extending elements". In particular, they partition each "element" into "components" and use two types of dependency models to calculate element reliability: the "point-site" model, where the element reliability equals that of the weakest component, and the "multi-site" model, where each element is treated as a series system and upper and lower reliability values are derived through the assumptions of independent and perfectly dependent components respectively. [41] account for four different types of interactions between different lifeline systems while [23] use functional and geographical interdependencies between five types of infrastructures to estimate the loss of service in a railway system. Finally, [17] consider two forms of dependency; a set-based one, where components belonging to different sets fail independently, and a vulnerability-based one, where components of the same dependency set are ordered from the strongest to the weakest. Failure of one component leads to the failure of all the weaker ones.

4.2.3. Performance Measures: No matter the underlying concept of PDNP, this should be transformed into a meaningful performance measure, which can be further used for evaluation and planning purposes. According to [38], performance measures may be categorized as *flow-dependent* or *flow-independent*, with the former attempting to capture congestion phenomena in the post-disaster stage whilst the latter requires only data on the physical state of the network. [11] argue that flow-dependent measures are of limited use in a post-disaster environment due to the lack of available data. In contrast, flow-independent measures avoid the inherent stochasticity of flow estimations in the aftermath of a disaster, focusing on easier-to-estimate parameters. The selection of the performance measure to use has a clear impact on the way the initial and the damaged state of the network component is described. [11] use three different flow-independent measures to estimate performance; total length of network open and total and areal distance-based accessibility. Component length participates in the calculation in all cases but under different concepts. The first measure is the fraction of the network open to traffic in the post-disaster stage in terms of length, irrespective of the actual allocation of the open segments and their connectivity. In the second measure, initial component length, damage state and connectivity are combined to provide an estimate of accessibility based on the minimum distance paths for every origin – destination (OD) pair. In the final measure the concept is similar, but accessibility is based on both minimum distance paths and weighting factors for the nodes according to pre-disaster OD data.

In a different approach, [55] decline the use of shortest distance paths as the appropriate measure for PDNP estimation. In their study, they assess the criticality of network links by reducing each time the capacity of one link and then performing a user equilibrium (UE) analysis. The performance measure developed is the sum of all arcs' travel times based on the UE results. The above indicate the significance of perspective in the final outcome of performance estimation. Even the same parameter (e.g. component length) when used under different frameworks can result in different performance estimates.

Another important observation is that the performance measure used is not always dictated by the type of analysis followed. For example, when the connectivity of a surviving network is investigated, an option would be that of connectivity reliability, focusing on the survival probabilities of the components. A typical example is the approach by [47] in which component failure probabilities are calculated based on estimates regarding their strength and the seismic loading they are subjected to. [40] on the other hand, combine connectivity reliability with generalized travel cost in a two-stage stochastic program aiming to allocate a certain budget for strengthening a highway network. Connectivity, however, has also been used in a vulnerability analysis context. Far from probability estimations, [29] examine connectivity from a topological point of view. They define OD-connectivity as the number of disjoint paths between an OD set when a number of links are disrupted. The selection of the distinct paths is based on acceptable travel time thresholds, with travel time remaining constant in the pre- and the post-disaster stage.

A wide variety of indices have been used for describing PDNP; these can be generally categorized as time-based, distance-based or cost-based. Accessibility, for instance, may be either a distance-based or a time-based measure whereas connectivity cannot be included in these categories. The literature has not indicated a trend in the use of specific performance measures in certain analysis types. In fact, the same measure can be used under different concepts or be combined with other ones (*e.g.*, [40]). Table 2 lists some of the indices encountered in the literature and assigns them to the papers reviewed. It is important to mention that accessibility and connectivity are presented in their general form and do not correspond to a unique index. Most measures are self-explanatory, while for the rest a brief description is the following: *Total network travel time* is the sum of all network users' travel time to reach their destination. *Total network travel time increase* (also referred to as *total travel time delays* or *total travel time loss*) is the difference between the pre- and post-disaster phase total network travel times.The terms *travel time* and *travel time increase* are similar in meaning to the aforementioned total travel time and total travel time increase but do not regard the whole network; instead, they may refer to a link, a path or an OD pair. *Network connectivity* is defined as the extent to which the nodes of a network remain connected after an incident or have become isolated. Along with *accessibility*, they are the two most usually encountered measures in the transportation network performance literature.

5. Discussion

The purpose of the first part of the survey of post-disaster transportation planning is to systematically present efforts on representing and estimating post-disaster network performance. As mentioned, this is the first necessary step before proceeding into modeling, analyzing and planning post-disaster transportation network operations. Reviewed papers were classified with respect to the disaster environment assumed and the conceptual approach towards describing the PDNP.

The disaster environment sets the status of the surviving network and it is defined based on the disaster, the network characteristics and the assumed failure representation. The review indicated that earthquakes are the most commonly considered disaster in this

type of studies, particularly in cases where PDNP estimation was disaster dependent. Indeed, the extensive research on the seismic events and the development of fragility curves makes earthquakes suitable for the estimation of failure probabilities and the respective damage states as opposed to making arbitrary assumptions regarding component failure. With respect to network characteristics, most papers consider roadway networks (either urban, regional or highway) but there is also a part of the bibliography dealing with bridge networks. The consideration of bridge networks is a common practice in papers investigating reinforcement or restoration strategies by assuming that failure is only probable and limited to them. Failure on the link level is generally treated in the form of capacity reductions and can be either complete or partial. In the case where fragility curves are used, failure is indicated by the expected damage state and the associated probability. Complete failure is generally treated as a safety-favorable assumption and implies the elimination of the component in the surviving network representation, therefore changing the connectivity settings. However, there is a number of studies stressing the importance of incorporating partial failure as a possible damage state due to it being more conceptually accurate and leading to more representative performance estimations. Accurate performance assessment though is also dependent on the assumptions made regarding the number of the damaged components as well as their spatial distribution on the network. Studies investigating all possible disruption scenarios are until now limited to the assumption of single-link failures [21]. On the other hand, multiple-link failures are treated as "scenario-specific" cases by either arbitrary assumptions or by means of Monte-Carlo simulation. This is due to the computational burden associated with the consideration of all possible disruption combinations, making such an attempt infeasible for large-scale networks.

Table 2. Network Performance Measures

		[44]	[9]	[13]	[15]	[21]	[27]	[28]	[33]	[34]	[48]	[51]	[54]	[56]	[6]	[7]	[17]	[4]	[23]	[40]	[50]	[20]	[29]	[31]	[32]
Performance Measures	Connectivity	*						*							*	*	*	*		*			*		*
	Accessibility							*					*			*									
	Total network travel time														*								*		
	Total network travel time increase		*			*								*							*	*		*	
	Travel time (link-, path-, OD-based)			*																					
	Travel time increase (link-, path-, OD-based)		*			*	*				*											*			
	Satisfied / unsatisfied demand					*			*										*						*
	Maximum total flow																								
	System surplus																								
	Other		*	*	*		*			*		*					*		*	*	*				

Table 2. Network Performance Measures (Continued)

		[35]	[55]	[43]	[12]	[24]	[25]	[26]	[52]	[1]	[22]	[41]	[49]	[53]	[42]	[46]	[10]	[11]	[39]	[47] (1999)	[3]	[38]	[16]	[36]	[2]
Performance Measures	Connectivity											*				*			*	*	*	*			*
	Accessibility				*				*				*	*			*	*							
	Total network travel time		*																						
	Total network travel time increase	*						*	*		*			*											
	Travel time (link-, path-, OD-based)						*			*															
	Travel time increase (link-, path-, OD-based)						*		*		*			*											
	Satisfied / unsatisfied demand																								
	Maximum total flow																					*			
	System surplus														*								*	*	
	Other			*		*				*	*							*	*		*		*		

The conceptual approach was sub-divided into the categories “type of analysis”, “dependencies” and “performance measures”. Five analysis types were identified: vulnerability, reliability, risk, robustness and resilience. Although terminology is not consistent across the literature, most researchers agree that vulnerability generally indicates the weaknesses of the network, being more concerned about the impact of an incident. Reliability on the other hand is more focused on the probability of a disruption than on its consequences. Risk is closely related to both concepts and is defined as the product of consequence and probability. Robustness is generally the opposite of vulnerability describing the strength of a network whereas resilience is defined as the network’s ability to return to its normal function after a disruption. Most studies make use of vulnerability and reliability as an analysis type. However, since reliability is based on probabilities, a false estimation of these may lead to inaccurate performance assessments [29]. The consideration of a specific analysis type does not pose any restriction on the performance measures used or the assumption of dependencies. In particular, dependencies between network components and their failure states will certainly be a field for further research in the future. The review revealed only eight papers accounting for some sort of dependency in their problem formulation. The type of disaster occurring interferes with dependencies mainly through the use of fragility curves for component damage estimation. Some studies though make arbitrary assumptions about the interaction of network components and its impact on their failure states. In any case, it must be noted that current studies do not capture the underlying parameters indicating the existence of an interaction but assume that there is one and attempt to model it. Irrespective of the dependency or independency assumptions, the estimation of network performance must be based on the use of specific performance measures. The literature provides a wide variety of measures broadly categorized as flow-dependent and flow-independent. The nature of the measure also indicates the way the initial and post-disaster network component state is described. Flow-dependent measures try to capture congestion

phenomena and have therefore a time parameter involved. Typical measures of this category include total network travel time and total network travel time increase. Similar formulations can also be made on the link level. The value of these measures, although significant from a theoretical perspective, may be limited in practice due to the uncertainties involved in post-disaster network flow estimations [11]. To avoid this pitfall, some researchers suggested the use of flow-independent measures, the most important being connectivity, with the term used here in its generic form. Another equally important measure is that of accessibility which can be either distance-based or time-based (flow-independent or flow-dependent respectively).

6. Conclusions and Future Steps

This two-part survey aims at offering a systematic and structured review of the literature related to post-disaster transportation network planning and management. In this context, existing work in the field is disaggregated into two distinct parts: estimation of transportation network performance and deployment of operations and actions for the management of the post-disaster phase. The present study focused on assessing the surviving network's performance. In total, forty eight papers were reviewed. Studies were classified according to general aspects of the problem's environment and their approach towards conceptualizing and modeling the problem. It must be noted that the inherent stochasticity of the disaster phenomena and their impact on the network along with the uncertain interaction mechanisms between the network components themselves and the traffic flows add to the problem's complexity allowing for different problem formulations; the combination of different problem parameters, types of analysis and performance measures is clearly dependent on and reflective of the authors' perspectives.

Despite the progress made, there is still research potential in the field of post-disaster network performance. Performance estimation depends greatly on the way post-disaster network states are realized in the model. Research gradually shifts to a more accurate representation of network conditions. The first step is the introduction of partial failures in model formulation (mainly in the form of road capacity reductions) even though complete failure models still exist as safety-favorable. In addition, from a topological point of view, the number of instantaneous component failures and their spatial distribution, therefore the actual form of the surviving transportation network, is an aspect deserving more attention in the future. Moreover, the independence assumption between network components and their failure states is bound to gradually fade away giving its place to the consideration of dependencies. The notion of dependency can also be expanded to capture interrelated disaster phenomena. The total impact on the network cannot be estimated by simply accumulating the consequences of the two phenomena as if the network was intact in both cases; performance estimation must be based on the fact that the network will have already suffered some damages to its elements due to the preceding catastrophe when the second disaster arrives.

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References

[1] H. Al-Deek and E. Emam, "New methodology for estimating reliability in transportation networks with degraded link capacities", Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, vol. 10, no. 3, **(2006)**, pp. 117–129.

[2] G. Augusti, A. Borri and M. Ciampoli, "Optimal allocation of resources in reduction of the seismic risk of highway networks", Engineering Structures, vol. 16, no. 7, **(1994)**, pp. 485–497.
[3] G. Augusti and M. Ciampoli, "Multi-objective optimal allocation of resources to increase the seismic reliability of highways", Mathematical Methods of Operations Research, vol. 47, no. 1, **(1998)**, pp. 131–164.
[4] J. Azevedo, L. Guerreiro, R. Bento, M. Lopes and J. Proença, "Seismic vulnerability of lifelines in the greater Lisbon area", Bulletin of Earthquake Engineering, vol. 8, no. 1, **(2010)**, pp. 157–180.
[5] K. Berdica, "An introduction to road vulnerability: what has been done, is done and should be done", Transport Policy, vol. 9, no. 2, **(2002)**, pp. 117–127.
[6] P. Bocchini and D. M. Frangopol, "A stochastic computational framework for the joint transportation network fragility analysis and traffic flow distribution under extreme events", Probabilistic Engineering Mechanics, vol. 26, no. 2, **(2011)**, pp. 182–193.
[7] F. Bono and E. Gutiérrez, "A network-based analysis of the impact of structural damage on urban accessibility following a disaster: the case of the seismically damaged Port Au Prince and Carrefour urban road networks", Journal of Transport Geography, vol. 19, no. 6, **(2011)**, pp. 1443–1455.
[8] M. Bruneau, S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace and D. von Winterfeldt, "A framework to quantitatively assess and enhance the seismic resilience of communities", Earthquake Spectra, vol. 19, no. 4, **(2003)**, pp. 733–752.
[9] W. Burgholzer, G. Bauer, M. Posset and W. Jammernegg, "Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model", Decision Support Systems, vol. 54, no. 4, **(2012)**, pp. 1580–1586.
[10] S. E. Chang, "Transportation planning for disasters: An accessibility approach", Environment and Planning A, vol. 35, no. 6, **(2003)**, pp. 1051–1072.
[11] S. E. Chang and N. Nojima, "Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective", Transportation Research Part A: Policy and Practice, vol. 35, no. 6, **(2001)**, pp. 475–494.
[12] A. Chen, C. Yang, S. Kongsomsaksakul and M. Lee, "Network-based accessibility measures for vulnerability analysis of degradable transportation networks", Networks and Spatial Economics, vol. 7, no. 3, **(2007)**, pp. 241–256.
[13] B. Y. Chen, W. H. K. Lam, A. Sumalee, Q. Li and Z.-C. Li, "Vulnerability analysis for large-scale and congested road networks with demand uncertainty", Transportation Research Part A: Policy and Practice, vol. 46, no. 3, **(2012)**, pp. 501–516.
[14] R. Church and M. P. Scaparra, "Analysis of facility systems' reliability when subject to attack or a natural disaster", Critical Infrastructure, Reliability and Vulnerability, Edited by A. T. Murray and T.H. Grubesic, Springer Berlin Heidelberg, **(2007)**, pp. 221–241.
[15] F. Cirianni, F. Fonte, G. Leonardi and F. Scopelliti, "Analysis of lifelines transportation vulnerability", Procedia - Social and Behavioral Sciences, vol. 53, **(2012)**, pp. 29–38.
[16] Z.-P. Du and A. Nicholson, "Degradable transportation systems: sensitivity and reliability analysis", Transportation Research Part B: Methodological, vol. 31, no. 3, **(1997)**, pp. 225–237.
[17] D. Günneç and F. S. Salman, "Assessing the reliability and the expected performance of a network under disaster risk", OR Spectrum, vol. 33, no. 3, **(2011)**, pp. 499–523.
[18] I. Hernandez-Fajardo and L. Dueñas-Osorio, "Probabilistic study of cascading failures in complex interdependent lifeline systems", Reliability Engineering and System Safety, vol. 111, **(2013)**, pp. 260–272.
[19] Y. Iida, F. Kurauchi and H. Shimada, "Traffic management system against major earthquakes", IATSS Research, vol. 24, no. 2, **(2000)**, pp. 6–17.
[20] E. Jenelius, "Network structure and travel patterns: Explaining the geographical disparities of road network vulnerability", Journal of Transport Geography, vol. 17, no. 3, **(2009)**, pp. 234–244.
[21] E. Jenelius and L.-G. Mattsson, "Road network vulnerability analysis of area-covering disruptions: A grid-based approach with case study", Transportation Research Part A: Policy and Practice, vol. 46, no. 5, **(2012)**, pp. 746–760.
[22] E. Jenelius, T. Petersen and L.-G. Mattsson, "Importance and exposure in road network vulnerability analysis", Transportation Research Part A: Policy and Practice, vol. 40, no. 7, **(2006)**, pp. 537–560.
[23] J. Johansson and H. Hassel, "An approach for modelling interdependent infrastructures in the context of vulnerability analysis", Reliability Engineering and System Safety, vol. 95, no. 12, **(2010)**, pp. 1335–1344.
[24] M. G. Karlaftis, K. L. Kepaptsoglou and S. Lambropoulos, "Fund allocation for transportation network recovery following natural disasters", Journal of Urban Planning and Development, vol. 133, no. 1, **(2007)**, pp. 82–89.
[25] A. Kiremidjian, J. Moore, Y. Y. Fan, O. Yazlali, N. Basoz and M. Williams, "Seismic risk assessment of transportation network systems", Journal of Earthquake Engineering, vol. 11, no. 3, **(2007)**, pp. 371–382.
[26] A. S. Kiremidjian, E. Stergiou and R. Lee, "Issues in seismic risk assessment of transportation networks", Earthquake Geotechnical Engineering, 4th International Conference on Earthquake

Geotechnical Engineering - Invited Lectures, Edited by K. D. Pitilakis, Springer Netherlands, vol. 6, **(2007)**, pp. 461–480.
[27] V. L. Knoop, M. Snelder, H. J. van Zuylen and S. P. Hoogendoorn, "Link-level vulnerability indicators for real-world networks", Transportation Research Part A: Policy and Practice, vol. 46, no. 5, **(2012)**, pp. 843–854.
[28] R. Kondo, Y. Shiomi and N. Uno, "Network evaluation based on connectivity reliability and accessibility", Network Reliability in Practice, Selected Papers from the 4th International Symposium on Transportation Network Reliability, Edited by D. M. Levinson, H. X. Liu and M. Bell, Springer New York, **(2012)**, pp.131–149.
[29] F. Kurauchi, N. Uno, A. Sumalee and Y. Seto, "Network evaluation based on connectivity vulnerability", In Transportation and Traffic Theory 2009: Golden Jubilee, Papers Selected for Presentation at ISTTT18, A Peer Reviewed Series since 1959, Edited by W. H. K. Lam, S. C. Wong and H. K. Lo, Sringer US, **(2009)**, pp.637–649.
[30] R. G. Little, "Controlling cascading failure: understanding the vulnerabilities of interconnected inftastructures", Journal of Urban Technology, vol. 9, no. 1, **(2002)**, pp. 109-132.
[31] C. Liu, Y. Fan and F. Ordóñez, "A two-stage stochastic programming model for transportation network protection", Computers and Operations Research, vol. 36, no. 5, **(2009)**, pp. 1582–1590.
[32] T. C. Matisziw and A. T. Murray, "Modeling s-t path availability to support disaster vulnerability assessment of network infrastructure", Computers and Operations Research, vol. 36, no. 1, **(2009)**, pp. 16–26.
[33] E. Miller-Hooks, X. Zhang and R. Faturechi, "Measuring and maximizing resilience of freight transportation networks", Computers and Operations Research, vol. 39, no. 7, **(2012)**, pp. 1633–1643.
[34] T. Nagae, T. Fujihara and Y. Asakura, "Anti-seismic reinforcement strategy for an urban road network", Transportation Research Part A: Policy and Practice, vol. 46, no. 5, **(2012)**, pp. 813–827.
[35] A. Nagurney and Q. Qiang, "A relative total cost index for the evaluation of transportation network robustness in the presence of degradable links and alternative travel behavior", International Transactions in Operational Research, vol. 16, no. 1, **(2009)**, pp. 49–67.
[36] A. Nicholson and Z.-P. Du, "Degradable transportation systems: an integrated equilibrium model", Transportation Research Part B: Methodological, vol. 31, no. 3, **(1997)**, pp. 209–223.
[37] D. A. Niemeier, "Accessibility: An evaluation using consumer welfare", Transportation, vol. 24, **(1997)**, pp. 377–396.
[38] N. Nojima, "Prioritization in upgrading seismic performance of road network based on system reliability analysis", Proceedings of the 3rd China-Japan-US Trilateral Symposium on Lifeline Earthquake Engineering, August, Kunming, China, **(1998)**.
[39] N. Nojima and M. Sugito, "Simulation and evaluation of post-earthquake functional performance of transportation network", Proceedings of the 12th World Conference on Earthquake Engineering, 12WCEE, Auckland, New Zealand, **(2000)** January 30– February 4.
[40] S. Peeta, S. F. Salman, D. Günneç and K. Viswanath, "Pre-disaster investment decisions for strengthening a highway network", Computers and Operations Research, vol. 37, no. 10, **(2010)**, pp. 1708–1719.
[41] K. Pitilakis, M. Alexoudi, S. Argyroudis, O. Monge and C. Martin, "Earthquake risk assessment of lifelines", Bulletin of Earthquake Engineering, vol. 4, no. 4, **(2006)**, pp. 365–390.
[42] H. Poorzahedy and S. N. S. Bushehri, "Network performance improvement under stochastic events with long-term effects", Transportation, vol. 32, no. 1, **(2005)**, pp. 65–85.
[43] Q. Qiang and A. Nagurne, "A unified network performance measure with importance identification and the ranking of network components", Optimization Letters, vol. 2, no. 1, **(2008)**, pp. 127–142.
[44] A. Reggiani, "Network resilience for transport security: Some methodological considerations", Transport Policy, vol. 28, **(2013)**, pp. 63-68.
[45] S. M. Rinaldi, J. P. Peerenboom and T. K. Kelley, "Identifying, understanding, and analyzing critical infrastructure interdependencies", IEEE Control Systems Magazine, vol. 21, no. 6, **(2001)**, pp. 11-25.
[46] H. Sakakibara, Y. Kajitani and N. Okada, "Road network robustness for avoiding functional isolation in disasters", Journal of Transportation Engineering, vol. 130, no. 5, **(2004)**, pp. 560–567.
[47] S. A. Selçuk and S. M. Yücemen, "Reliability of lifeline networks under seismic hazard", Reliability Engineering and System Safety, vol. 65, **(1999)**, pp. 213–227.
[48] M. Snelder, H. J. van Zuylen and L. H. Immers, "A framework for robustness analysis of road networks for short term variations in supply", Transportation Research Part A: Policy and Practice, vol. 46, no. 5, **(2012)**, pp. 828–842.
[49] J. Sohn, "Evaluating the significance of highway network links under the flood damage: An accessibility approach", Transportation Research Part A: Policy and Practice, vol. 40, no. 6, **(2006)**, pp. 491–506.
[50] J. L. Sullivan, D. C. Novak, L. Aultman-Hall and D. M. Scott, "Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach", Transportation Research Part A: Policy and Practice, vol. 44, no. 5, **(2010)**, pp. 323–336.
[51] P. Tamvakis and Y. Xenidis, "Resilience in transportation systems", Procedia - Social and Behavioral Sciences, vol. 48, **(2012)**, pp. 3441–3450.

[52] M. A. P. Taylor and G. M. D' Este, "Transport network vulnerability : A method for diagnosis of critical locations in transport infrastructure systems", Critical Infrastructure, Reliability and Vulnerability, Edited by A. T. Murray and T.H. Grubesic, Springer Berlin Heidelberg, **(2007)**, pp. 9–30.
[53] M. A. P. Taylor, S. V. C. Sekhar and G. M. D'Este, "Application of accessibility based methods for vulnerability analysis of strategic road networks", Networks and Spatial Economics, vol. 6, no. 3-4, **(2006)**, pp. 267–291.
[54] M. A. P. Taylor and Susilawati, "Remoteness and accessibility in the vulnerability analysis of regional road networks", Transportation Research Part A: Policy and Practice, vol. 46, no. 5, **(2012)**, pp. 761–771.
[55] S. V. Ukkusuri and W. F. Yushimito, "A methodology to assess the criticality of highway transportation networks", Journal of Transportation Security, vol. 2, no. 1-2, **(2009)**. pp. 29–46.
[56] L. Yang and D. Qian, "Vulnerability analysis of road networks", Journal of Transportation Systems Engineering and Information Technology, vol. 12, no. 1, **(2012)**, pp. 105–110.
[57] R. Zimmerman, "Social implications of infrastructure interactions", Journal of Urban Technology, vol. 8, no. 3, **(2001)**, pp. 51-60.
[58] C. Zimmerman, R. Brodesky and J. Karp, "Routes to effective evacuation planning primer series: Using highways for no-notice evacuations", Federal Highway Administration, US Department of Transportation, Report No. FHWA-HOP-08-003, **(2007)**.
[59] R. Zimmerman and C. E. Restrepo, "The next step: quantifying infrastructure interdependencies to improve security", Journal of Critical Infrastructures, vol. 2, no. 2-3, **(2006)**, pp. 215-230.
[60] C. W. Zobel, "Comparative visualization of predicted disaster resilience", Proceedings of the 7th International ISCRAM Conference, Seattle, Washington, USA, **(2010)** May 2-5.
[61] C. W. Zobel, "Representing perceived tradeoffs in defining disaster resilience", Decision Support Systems, vol. 50, no. 2, **(2011)**, pp. 394–403.
[62] C. W. Zobel and L. Khansa, "Characterizing multi-event disaster resilience", Computers and Operations Research, vol. 42, **(2014)**, pp. 83-94.

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